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Heat Transfer And Aerodynamics Of A High Rim Speed Turbine Nozzle Guide Vane With Profiled End Walls

by

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SUMMARY

It has been shown that the secondary flows present within turbine nozzle guide vanes have a marked effect on heat transfer. The horse-shoe and passage vortices, for example, have a major impact on platform and vane suction surface heat transfer. To investigate these effects further, heat transfer and aerodynamic measurements have been made on an annular transonic turbine nozzle guide vane ring, with three different platform geometries. The measurements were taken in the Isentropic Light Piston test facility at RAE Pyestock at representative values of engine Reynolds number, Mach number and freestream gas-to-wall temperature ratio.

This paper compares and discusses the measured platform and vane suction surface Nusselt and Mach number distributions for the three different endwall profiles. Comparisons with theoretical flow and heat transfer predictions are presented.

A paper presented at the American Society of Mechanical Engineers Gas Turbine and Aeroengine Conference, Cologne, June 1992.

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ABSTRACT

It has been shown that the secondary flows present within turbine nozzle guide vanes have a marked effect on heat transfer. The horse-shoe and passage vortices, for example, have a major impact on platform and vane suction surface heat transfer. To investigate these effects further, heat transfer and aerodynamic measurements have been made on an annular transonic turbine nozzle guide vane ring, with three different platform geometries. The measurements were taken in the Isentropic Light Piston test facility at RAE Pyestock at representative values of engine Reynolds number, Mach number and freestream gas-to-wall temperature ratio.

This paper compares and discusses the measured platform and vane suction surface Nusselt and Mach number distributions for the three different endwall profiles. Comparisons with theoretical flow and heat transfer predictions are presented.

1. INTRODUCTION

There is a general need to increase peak turbine temperatures in future gas turbine engines in order to offer improved performance. For military engines, higher peak temperatures give improved thrust to weight ratio and with combustor fuel/air ratios approaching stoichiometric there may be less freedom to control the combustor exit temperature profile, leading to significantly higher gas temperatures near the endwalls. For civil transport engines, lower specific fuel consumption is a major goal and higher cycle temperatures can offer improved thermal efficiency (in conjunction with higher cycle pressure ratio). In all engines the turbine cooling flow quantities should be minimised because they are a penalty to the cycle. Hence there is a strong need to design better cooling systems, particularly on the turbine endwalls. This will offer the benefits of higher cycle temperature and the option of longer blade lives. There are also significant benefits of more capable design methods in the development of new or improved engines in reduced development risk and cost. In order to achieve better design methods, more detailed information is required on the heat transfer to the endwall surfaces between the vanes. In this region, the heat flux is highly non-uniform because of the presence of complex three-dimensional secondary flows, making the turbine designer's task very difficult. Profiling of the endwall is one factor that could be used in the design process to control the flow and heat transfer. To investigate this, an annular cascade test was therefore carried out with three different endwall profiles and the results compared with prediction.

2. ENDWALL FLOW PHENOMENA

Two-dimensional cascade measurements (York et al, 1983, Gladden et al, 1988 and Boyle et al, 1989) have investigated general features of the endwall flow but without modelling the radial pressure gradient. A number of the general features are illustrated in Figure 1 and described below.

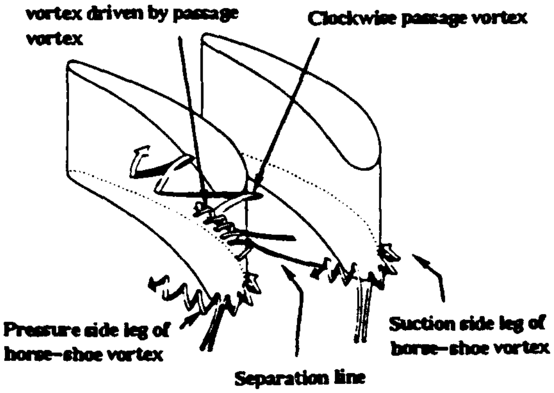

Fig 1 3-D Cascade Flow Structure

The inlet endwall boundary layer stagnates at the vane leading edge and forms a horse-shoe vortex. The two legs of this vortex, on the pressure and suction sides, proceed into the two adjacent passages. The pressure side leg is swept across the endwall by the passage secondary vortex to the suction side and then up the vane suction surface. This causes the boundary layer to be stripped off the endwall and convected to the suction side of the passage and then up the suction surface of the vane. A new thin highly skewed boundary layer thus forms behind the separation line, which results in high heat transfer in this region. The suction side leg stays close to the vane surface. Earlier annular testing by Granziani et al, 1979, and Gaugler and Russell, 1983, made a detailed attempt to relate secondary flow to measured heat transfer patterns. However, the work was not representative of engine operating conditions in terms of Reynolds number, Mach number and gas-to-wall temperature ratio. As with other researchers they concluded:

- endwall heat transfer is significantly affected by the horse-shoe vortex generated at the leading edge and subsequently by the evolution of secondary flow

- high leading and trailing edge heat transfer and large cross passage heat transfer gradients are present.

Little heat transfer data on annular configurations at engine representative conditions are available. Thus, the need to understand factors governing endwall heat transfer is still of continuing importance.

3. FEATURES OF PROFILED ENDWALL AND VANE DESIGN

An investigation has been undertaken at RAE of the potential benefits of profiling the hub endwall of the nozzle guide vanes (Horton et al, 1991). Three different profile shapes have been investigated experimentally, comprising a Bellmouth profile and two S-bend shapes as shown on Figure 2.

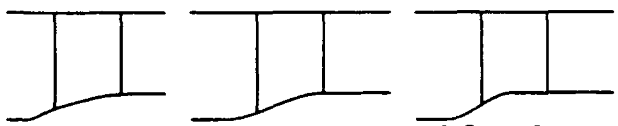

Fig 2 Hub Profile Shapes

The aim of these endwall shapes was to reduce the secondary effects by re-energising the flow near the endwall. The distribution of curvature, and hence the local acceleration provided to the flow, varied between the designs. The endwall profiling was present only on the hub. This enabled the effect on the flow near the unprofiled casing to be examined.

The vane used is a high turning ngv, the High Rim Speed Turbine (HRST) (Kingcombe et at, 1989). It features a variation of exit flow angle along the span and a curved tangential stack of the trailing edge to control secondary flows by setting up spanwise pressure gradients. At the design condition the exit hub Mach number is 1.14 and the Reynolds number (based on hub exit conditions and true chord) is 3.4 x 10^6. The original ngv was designed for cylindrical endwalls.

This paper presents the results from an experimental programme of testing undertaken to determine the endwall heat transfer and static pressure distribution on an annular cascade of ngvs with the three different endwall profiles. The three profile shapes feature:-

Bellmouth:- the concave curvature is confined to a small region upstream of the leading edge, with convex curvature all the way through the vane passage to the throat.

S-bend 1:- a forward S-bend, a cubic curve joins the parallel upstream and downstream sections.

S-bend 2:- as S-bend 1 but the concave curvature all occurring ahead of the leading edge.

Heat transfer results were obtained on the endwall, on the inner fillet radius and on the vane suction surface at 10% annulus height. Static pressure measurements were also taken at the same locations as well as at 50% annulus height. The heat transfer results are presented in terms of Nusselt number distribution for the three hub shapes, where Nusselt number is the surface heat transfer coefficient multiplied by true aerofoil chord and divided by the thermal conductivity of air. The static pressure distribution is presented in terms of isentropic Mach number calculated from the measured static pressure and upstream total pressure.

A three-dimensional Navier-Stokes flow solver (Dawes, 1986) was used to predict Mach number distributions for all profiles, at the design Reynolds and Mach number. For endwall heat transfer distribution, a preliminary prediction was carried out using a modified version of STAN5 (Crawford and Kays, 1976) to predict Nusselt number on the Bellmouth hub profile.

4. TEST FACILITY AND INSTRUMENTATION

Testing was carried out in the Isentropic Light Piston Cascade (ILPC) at RAE Pyestock. This is a short duration facility designed to allow high quality heat transfer and aerodynamic measurements to be taken for a full-size annular cascade of turbine vanes. The use of this technique for turbomachinery measurements was pioneered by Schultz et al, (1973). The Pyestock facility is described by Brooks et al, (1985). A schematic view of the ILPC is shown in Figure 3.

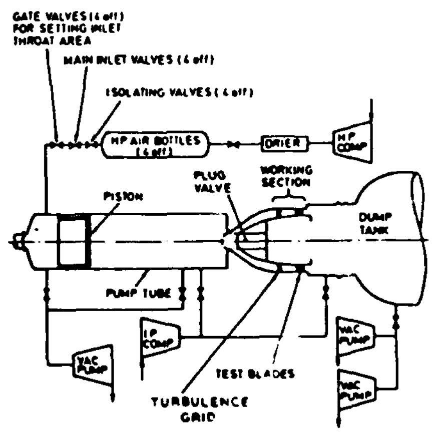

Fig 3 ILPC Test Facility

A light-free piston is forced along a tube by high pressure air and compresses and thereby heats the air ahead of it. When a predetermined level of pressure is reached, a fast acting valve opens allowing the heated air to flow through the working section and into a dump tank. This gives steady operating conditions for the duration of the run, which can be varied from about 0.5 to 1.0 sec depending on the rise in air temperature required. The test conditions can be matched to engine values of both Reynolds number and Mach number. Engine values of gas-to-wall temperature ratio are also matched. A major extension of the facility, to enable heat transfer data to be taken from a rotating rotor mounted downstream of the nozzle row, has been designed and is being installed.

For heat transfer measurements the ngv's are manufactured from machinable glass (Corning Macor)[1] which has a low thermal diffusivity, on which are painted thin film gauges. The rapid change in surface temperature measurement during an ILPC run is converted to heat transfer rate by an electrical analogue circuit which solves the one-dimensional transient heat conduction equation (Oldfield et al, 1984). The output signal is then digitised and recorded on a mini computer.

The distribution of static pressure on the ngv's was measured using surface tappings, and the inlet total pressure was determined using a five point rake. The pressure signals were recorded using a fast-acting Scanivalve[2] ZOC (Zero, Operate, Calibrate) system.

The overall accuracy for the heat transfer results is within ± 5%. For the aerodynamic results the isentropic Mach numbers calculated from the measured static pressures are accurate to within ± 0.1% for transonic flow conditions. At low flow velocities the error is significantly larger, representing about 10% at 0.1 Mach number due to the sensitivity of Mach number to static pressure. All tests were performed with a turbulence grid at 4.5 axial chords upstream of the ngv's, giving an inlet turbulence level of 6.5% as measured with a hot-wire anemometer. Table 1 shows details of the ngv operating conditions and geometry.

Test Operating Conditions

Exit Mach number	1.14 ± 2%
Exit Reynolds number	3.4E6 ± 2%
Gas-to-wall temperature ratio, T_g/T_w	1.5 ± 2%
Inlet turbulence	6.5%

Vane Geometry

Scale	1.3
Tangential chord	74.5 mm
Axial chord	39.1 mm
Aspect ratio	1.17
Space/chord ratio	0.78

OPERATING CONDITIONS AND GEOMETRY
(Values at Hub)

Table 1

5. EXPERIMENTAL AND COMPUTATIONAL RESULTS

5.1 Flow Field Comparison

The measured vane suction and pressure surface isentropic Mach number distribution at 10% and 50% span are shown in figure 4 for the three hub profiled shapes. In comparing the S-bend and Bellmouth distributions at 10% span, the S-bend 2 profile has increased the Mach number on the early part of the suction surface and slightly increased shock strength, at approximately 70% axial chord. The S-bend 1 has a lower Mach number earlier, but then slightly increased just

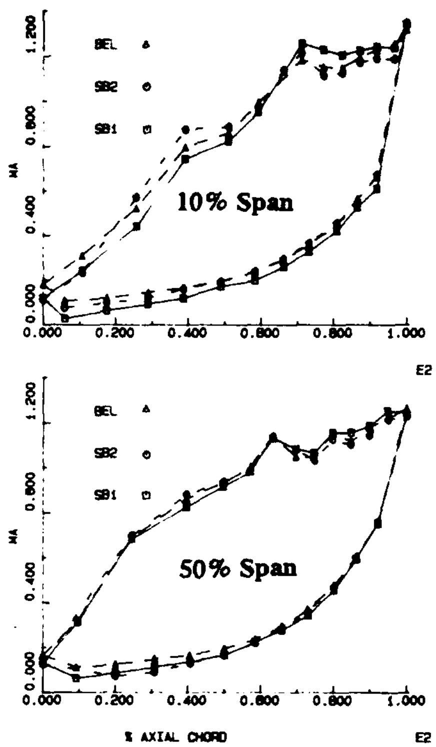

Fig 4 Mach Number Distribution

before the shock. The shock is weaker than on S-bend 2. The effect on the pressure surface is very small. At 50% span there is very little difference between the three measured results. Previous work (Horton et al, 1991) has shown that these measurements agree with predictions of the flow using the Dawes 3-dimensional flow solver.

Measured and predicted hub Mach numbers are shown in figure 5 for all three profiled endwall shapes. Comparing the measured distribution of Mach number the S-bend 1 and Bellmouth profiles look quite similar, whereas S-bend 2 has an area of lower acceleration migrating from the pressure side towards the suction side, starting at about 50% downstream of the leading edge but not arriving at the suction side until late in the passage. This pattern is just detectable on the Bellmouth profile, starting a little earlier and getting less evident further downstream but moving across more rapidly than on S-bend 2. On the S-bend 1 hub, the effect is seen to be much weaker and more delayed, starting near the pressure side trailing edge and rapidly crossing towards the suction side. Summarising, the secondary flow migration is weakest with S-bend 2, and arrives at the suction side earlier with Bellmouth and S-bend 1.

The predictions presented were carried out with the Dawes 3D Navier-Stokes flow solver (Dawes, 1986), using a grid of 74 axial, 25 radial, 25 tangential points on a sheared H grid. All computations were perfomed at the design Reynolds and Mach number. The predictions show similar features to the experiments. Previous predictions (Horton, 1991) showed that the passage cross flow on the hub impinges on the suction surface slightly further downstream with the two S-bend profiles than with the Bellmouth. Figure 5 shows very good agreement between the predicted and measured isentropic Mach number distributions.

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[1] Corning Macor - Trademark of Corning Macor Glass, Corning, USA

[2] Scanivalve - Trade mark of Scanivalve Corp, San Diego, USA

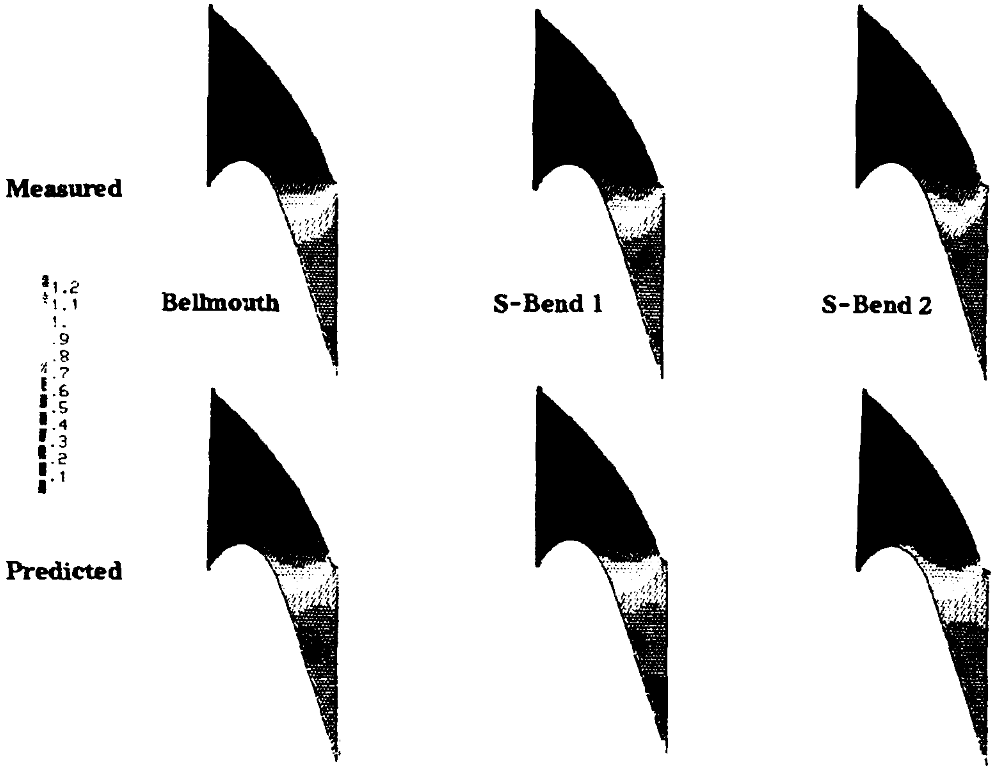


Fig 5 Measured & Predicted Hub Mach Numbers

Figure 6 shows measured Mach numbers on the casing; it can be seen that there is no significant difference between the measurements for the three hub profiles. Hence the outer wall is not influenced by the hub profiling, which is consistent with predictions of the flow.

5.2 Heat Transfer Comparison

The primary heat transfer results consist of Nusselt number distributions over the vane at 10% span, the hub fillet radius and over the entire endwall region. Figure 7 shows measured vane Nusselt number at 10% span for the three profile shapes. No significant difference is seen between the three profiles. This is also true of the inner fillet radius Nusselt number distribution. Figure 8 shows Nusselt number distributions on the three hub profiles. Unlike the Mach number distributions these show quite different patterns from each other. The Bellmouth profile has a peak in the mid passage near the pressure side trailing edge plane. This is similar to the S-bend 1 profile, but S-bend 2 has a very different pattern of Nusselt number. The peak here is close to the pressure side trailing edge and there is much lower heat transfer near the suction surface. This would indicate a lesser effect of secondary flow migration towards the suction side, at least in the mid passage region which is consistent with the isentropic Mach number results. Only the pressure side

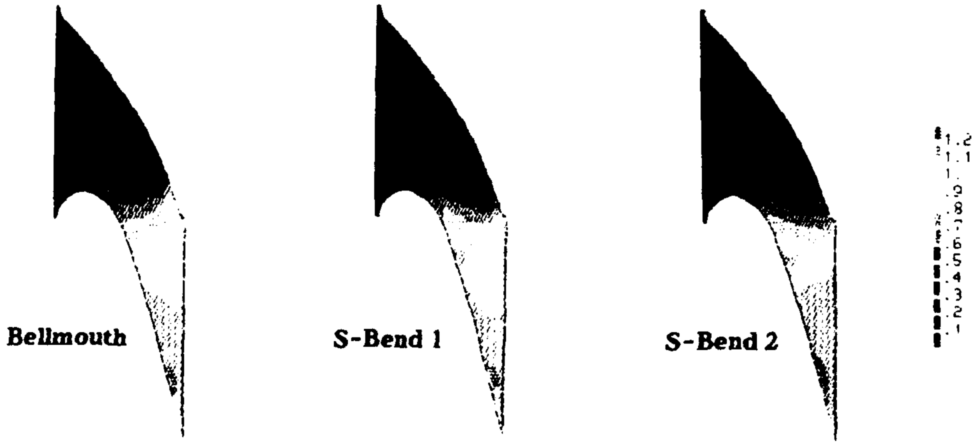


Fig 6 Measured Casing Mach Numbers

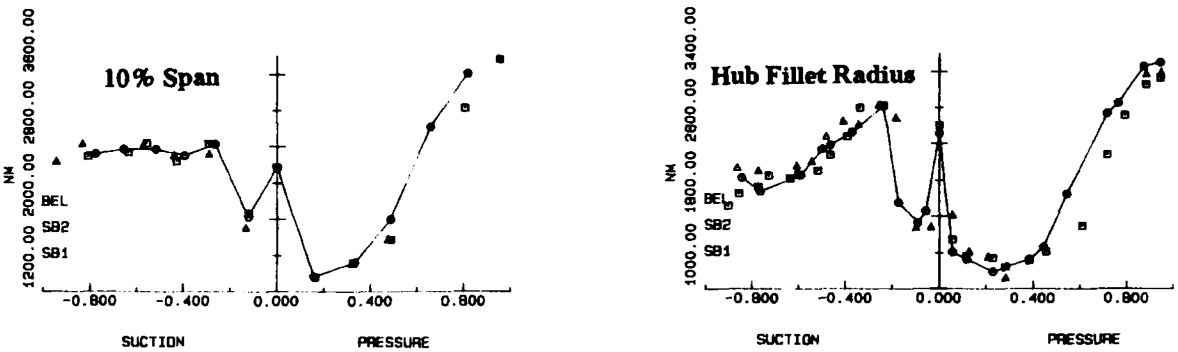


Fig 7 10% Span & Hub Fillet Radius Nusselt Number Distribution

trailing edge region has a high heat transfer. On S-bend 1 and Bellmouth the cross flow occurs fairly early in the passage so that a new thinner boundary layer is covering the remaining passage, giving high heat transfer near the suction side downstream of the separation line on the endwall. As the boundary layer thickens further downstream the heat transfer is reduced. This effect is only seen very close to the trailing edge on S-bend 2, the remaining passage showing little change in heat transfer.

The casing Nusselt number distributions, Figure 9, show no difference between the three profiles again suggesting no influence from the hub profile.

An attempt has been made to compute the heat transfer to the hub endwall for the Bellmouth profile. Figure 8 shows the predicted hub Nusselt number distribution. The prediction was performed using a modified version of the STAN5 boundary layer code (Crawford and Kays, 1976). The code was run

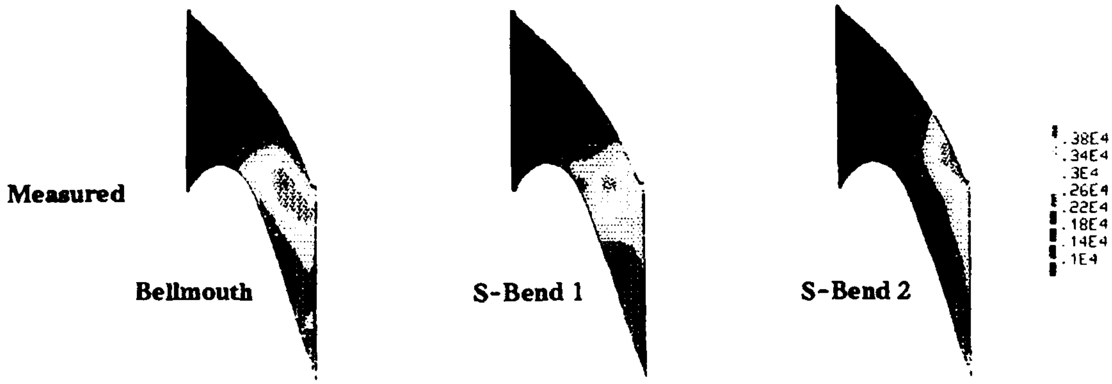
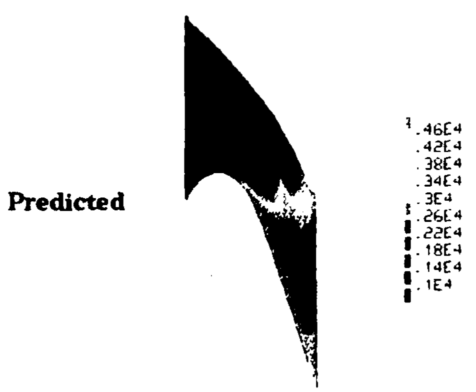


Fig 8 Measured & Predicted Hub Nusselt Numbers



using the predicted velocity distribution from 3D Dawes. Two-dimensional calculations were performed along grid lines on the endwall; there is no allowance for cross flow or surface curvature in this prediction. The inlet turbulence level was set at 6.5% and the inlet endwall boundary layer was assumed to be fully turbulent. It was recognised that this would over-predict heat transfer in regions of laminar and transitional flow. The region of peak heat transfer is predicted well although the Nusselt numbers are over-predicted by about 20%. All the contours are seen to be concentrated around the shock region, because the calculation along grid lines indicates that the boundary layer separates here. In practice, there is considerable cross-flow present in this region so that calculating along grid lines is not likely to be very accurate. Although this approach can be used to give an indication of the overall heat load on the endwall, it is not likely to yield an accurate distribution of heat transfer. An alternative approach is to calculate along skewed streamlines on the endwall (Harvey et al, 1990). In his case this yielded a considerably better predicted heat transfer distribution.

6. CONCLUSIONS

Heat transfer and aerodynamic measurements have been made on a fully annular transonic turbine nozzle guide vane, at engine

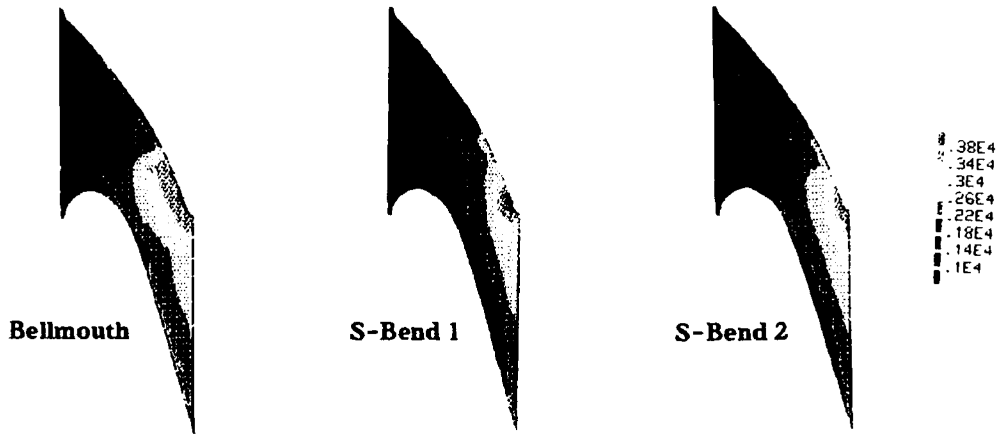


Fig 9 Measured Casing Nusselt Numbers

representative conditions with three endwall hub profile shapes.

The 3D Dawes Navier-Stokes flow solver has been used successfully to predict endwall isentropic Mach numbers on the three different profiled endwalls.

The flowfield phenomena inferred from the static pressure measurements agree with those required to describe the heat transfer measurements.

The three endwall hub profile shapes gave significantly different secondary flow patterns. The results suggest that the S-bend 2 profile gave less cross flow with a later separation line on the endwall. However, the peak heat transfer levels remained similar, S-bend 2 giving a different distribution with the region of peak heat transfer closer to the trailing edge.

All of the measurements and predictions indicate that the endwall profiling has no effect on the opposite endwall.

Heat transfer calculations with the 2-dimensional STAN5 finite difference, boundary layer code along grid lines on the endwall predicted values around 20% higher than the experiment. With this calculation, which did not include any allowance for cross flow, the boundary layer was predicted to separate at the location of the passage shock. Further work is required to obtain more accurate predictions and a better distribution on the endwall.

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REFERENCES

Boyle, R.J; Russell, L.M. — "Experimental determination of stator endwall heat transfer" ASME Paper 89-GT-219, 1989

Kingcombe, R.C.; Harasgama, S.P.; Leversuch, N.P.; Wedlake, E.T. — "Aerodynamic and heat transfer measurements on blading for a high rim-speed Transonic turbine" ASME Paper 89-GT-228, 1989

Gaugler, R.E.; Russell, L.M. — "Comparison of visualised turbine endwall secondary flows and measured heat transfer patterns" NASA Technical memorandum - TM 83016, 1983

York, R.E.; Hylton, L.D.; Mihelc, M.S. — "An experimental investigation of endwall heat transfer and aerodynamics in a linear vane cascade" ASME Paper 83-GT-52, 1983

Horton, G.C.; Harasgama, S.P.; Chana, K.S. — "Predictions and measurements of three-dimensional viscous flow in a transonic turbine nozzle guide vane" AGARD CPP Paper 19, 1991

Granziani, R.A.; Blair, M.F.; Taylor, J.R.; Mayle, R.E. — "An experimental study of endwall and airfoil surface heat transfer in a large scale turbine blade cascade" ASME Paper 79-GT-99

York, R.E.; Hylton, L.D.; Mihelc, M.S.; Turner, E.R — "Experimental investigations of turbine endwall heat transfer" Final reports I-III Aero Propulsion Labs, Wright Patterson Air Force Base, AFWAL TR-81-2077, 1981

Schultz, D.L.; Jones, T.V. — "Heat transfer measurements in short duration hypersonic facilities" AGARD-AG-165, 1973

Dawes, W.N. — "A numerical method for the analysis of three-dimensional viscous compressible flow in a turbine cascade: application to secondary flow development in a cascade with and without dihedral" ASME Paper 86-GT-145, 1986.

Crawford, M.E.; Kays, W.M. — "STAN5 a program for numerical computation of two dimensional internal and external boundary layers" NASA-CR 2742, 1976

Oldfield, M.L.G.; Burd, H.J.; Doe, N.C. — "Design of wide bandwidth analogue circuits for heat transfer instrumentation in a transient tunnel" 16th Symposium of ICHMT, Hemisphere Publication, Dubrovnik, 1982

Brooks, A.J. et al — "The isentropic light piston cascade at RAE Pyestock" AGARD-CP-390, 1985

Gladden, H.J.; Simoneau, R.J. — "Review and assessment of the database and numerical modelling for turbine heat transfer" 33rd ASME International Gas Turbine Congress, 1988

Harvey, N.W.; Jones, T.V. — "Measurement and calculation of endwall heat transfer and aerodynamics on a nozzle guide vane in annual cascade" ASME Paper 90-GT-301

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